IV. *On the Nature of the Streamers in the Electric Spark.*

By S. R. MILNER, *D.Sc. (Lond.), Lecturer in Physics in the University of Sheffield.*

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[PLATES 2–4.]

WHEN the oscillating electric spark is examined in a rapidly rotating mirror, the successive oscillations render themselves evident in the image as a series of luminous curved streamers which emanate from the poles and extend towards the centre of the spark gap. These streamers were first observed by FEDDERSEN* in 1862, but the work of SCHUSTER and HEMSALECH† in 1900 may be said to have opened up a new era in the subject. These workers threw the image of the spark on the slit of a spectroscope, and photographed the resulting spectrum on a film which was maintained in rapid rotation in a direction at right angles to that of the incident light. In their photographs they found that the air lines extended straight across from pole to pole, but that the metal lines were represented by curved bands drawn out in the centre of the spark gap. There is a close relation between these bands and the streamers seen in the unanalysed inductive spark. SCHUSTER and HEMSALECH carried out their experiments with the smallest possible inductance in series with the spark, and thus made the period of the oscillations so small that the drawing out on the film was insufficient to separate the individual oscillations from each other. Thus their curved lines represent a composite structure, consisting of all the streamers due to the successive oscillations superposed on each other. It follows from their results that the light of the streamers in the spark is entirely produced by the glowing of the metallic vapour of the electrodes, and that, while the luminosity of the air is practically instantaneous in its occurrence, that due to the metal vapour occurs in the centre of the spark gap an appreciable time later than near the poles.

The actual process which goes on in the spark and gives rise to this delay in the arrival of the metallic vapour at the centre of the gap is not yet thoroughly understood. SCHUSTER and HEMSALECH make the natural supposition that it is due to the fact that the metal of the electrode is vaporised and rendered incandescent by the heat of the spark, and that the vapour takes an appreciable time to diffuse from

* 'Pogg. Ann.,' vol. 116, p. 132 (1862).

† 'Phil. Trans.,' A, vol. 193, p. 189 (1900).

the electrodes to the centre of the gap. The exception which has been taken to this view has arisen in part from the difficulty of observing the Doppler effect on the metallic lines which should be a concomitant of the diffusion of the vapour from the poles,* and in part from the extraordinary results which the authors themselves obtained in some metals for the velocity of the diffusion corresponding to the different lines. In the case of bismuth and, in a less degree, of cadmium the different metallic lines could be divided into groups of different curvatures which indicated different velocities of diffusion towards the centre of the gap. As regards the former matter, there does not seem to be involved any real difficulty to the explanation, as Dr. SCHUSTER has himself recently shown.† The curious effect of the different curvatures of the lines of the same element has, however, always remained more or less of a difficulty in the way of a complete acceptance of their view. SCHUSTER and HEMSALECH themselves refer to the possibility in the case of bismuth that the metal may be a compound, and that the two kinds of molecules give rise to the differently curved lines. Other explanations‡ have been made by different writers, but it cannot be said that any explanation adequately supported by experiment has been forthcoming. In view of this incompleteness in our knowledge of the constitution of the streamers it seemed to me that further observations with a rotating mirror would possibly be of value, and the investigations recorded below succeed, I think, in throwing a clearer light on the nature of the streamers, and on certain other phenomena which are characteristic of the spark.

In the first experiments which were made the light of the spark was not submitted to spectral analysis, but was observed as simply drawn out by the rotating mirror. While they were only of a preliminary nature they nevertheless gave some interesting results which merit a short description. The sparks were obtained by the discharge of a battery of 12 Leyden jars which were charged by an induction coil worked by a mercury platinum break. By means of a length of insulated copper wire, wound on a cylindrical rod and containing terminals along its length, varying amounts of inductance could be inserted in the discharging circuit. The poles between which the spark took place were pointed metal rods, held in corks and placed, one vertically above the other, in a small box with a single opening which cut off all light from the room except that by which the spark was examined. At its focal distance away from the spark was placed a large lens throwing the light in a parallel beam on to the rotating mirror, by which it was reflected on to the lens of an ordinary half-plate camera. The mirror was fixed on the axle of a gear-wheel arrangement, and could be rotated about a vertical axis by a motor at speeds up to about 150 rotations per second. The induction coil gave one or two sparks every second, of which perhaps one in every dozen was reflected into the camera. By looking through the back of the plate in the

* HULL, 'Astrophysical Journal,' vol. 25, p. 1 (1907).

† 'Astrophysical Journal,' vol. 25, p. 277 (1907).

‡ *Cf.* J. J. THOMSON, 'Conduction of Electricity through Gases,' p. 397; p. 520 in 2nd edition (1906).

camera while keeping control of the shutter, it was possible to expose for the few seconds required to just catch one or two good images on the plate and yet avoid the confusion of many overlapping ones.

The appearance of the drawn-out spark obtained with a small inductance (0·0001 henry) in circuit is shown in the photograph, fig. 1, Plate 2. We see the initial air discharge extending straight across from pole to pole, and succeeding it the streamers, starting from the poles and crossing each other in blurred masses in the centre of the spark gap. The streamer corresponding to each oscillation is observed to be much more prominent at one pole than at the other; this fact was noted both by FEDDERSEN and by SCHUSTER and HEMSALECH, but they were unable to determine from their photographs whether it was the positive or the negative pole from which the main streamer started. SCHENCK,* who subsequently investigated the spark by means of a rotating mirror, observed that the streamers came from the cathode in each case. HEMSALECH,† in a later research on the spark in which he separated the oscillations by blowing a current of air across them, found that it was from the positive pole that the streamers emanated. In each of my experiments the direction of the first discharge of the spark was determined by noting the direction of the discharge produced by the induction coil through an X-ray tube; the nature of the poles in the subsequent oscillations could then be easily ascertained by counting from the first discharge. In all the photographs, which comprise different metals, inductances, and capacities, and also different lines of the same element, I find, in agreement with SCHENCK, that in every case it is the cathode from which the stronger streamer emanates. There is, however, in all cases a tendency to a discharge from the anode. In the softer metals, such as magnesium and lead, this becomes very pronounced and nearly as strong as the cathode discharge. (See fig. 2, Plate 2, a spark between magnesium terminals.) With regard to HEMSALECH's result it is to be observed that he worked with much more inductance in the circuit than either SCHENCK or myself, and it is possible that his different result is due to the conditions in his experiments being more analogous to those obtaining in the arc than in the ordinary spark.

An interesting point was noticed in several of the photographs which throws a clear light on the nature of the streamers. This is illustrated in figs. 3, 4, and 5 (Plate 2). These photographs show oscillations of some of the streamers which represent backward and forward motions of the vapour forming them which are exactly synchronous with the oscillations of the spark itself.‡

* 'Astrophysical Journal,' vol. 14, p. 116 (1901).

† 'Comptes Rendus,' vol. 142, p. 1511 (1906).

‡ The sparks reproduced in figs. 3, 4, and 5 were taken in a magnetic field as described on p. 75. The magnetic field, while having nothing to do with the production of these oscillations, generally makes them more prominent, as the irregular course of the streamers produced by the field, which is referred to on p. 75, prevents them overlapping in the centre of the spark gap. It thus happened that these negatives showed the oscillations best, but the backward motion of the vapour is shown by many of my negatives of sparks without a field.

In their work on the inductionless spark, Messrs. SCHUSTER and HEMSALECH have observed an effect in the case of cadmium which is apparently somewhat similar to the above. Some of the metallic lines showed a wavy outline, which presumably indicated that the vapour had a velocity which alternately decreased and increased as it receded from the pole. This led them to suggest in 1900 the possibility that the metallic vapour was charged and carried the electric current, but the effect was not sufficiently marked in their photographs to enable them to make any definite assertion in this respect. SCHENCK later, in 1901,* showed that the streamers could not be the actual carriers of the current, as they do not proceed more than a short distance across the spark gap before the electrical discharge becomes reversed.

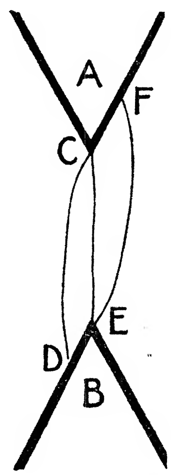
My photographs are therefore important, as the fact that the luminous vapour actually *comes back* towards the pole when the electric field of the spark reverses its direction forms so much definite evidence that the particles of which it is composed must be charged. This suggests that modifications may be called for in our view of the nature of the streamers. While one view of their constitution is that they are due to purely thermal diffusion and incandescence of the vapour of the electrode metal, another one possible is that they are mainly produced by the luminescence of charged atoms suddenly torn off from the surface of the electrode, and propelled towards the centre of the spark gap by the intense electric field of the spark; and the photographs support the second of these conceptions. This view has the advantage of relieving us of the necessity of making any hypothesis as to the temperature of the spark, for it is not difficult to imagine that the sudden release from strain which would occur as the atoms are torn off from the surface of the metal might give rise to the vibrations which correspond to the characteristic metal lines of the spark, apart from any thermal incandescence of the vapour. It is clear, however, that the electric force of the spark is not by itself capable of tearing off the atoms from the surface of the electrode, for the force exists before the spark begins to pass. But when the discharge has actually begun the metal surface is being bombarded by the ions which carry the current, and this bombardment also is doubtless an essential factor in the disruption of the surface and the production of the luminescence. This view perhaps suggests a reason why the streamers are so much more vigorous at the negative than at the positive electrodes, if we suppose that the positive ions which carry the current of the spark are more efficient in causing disruption of the surface than are the (probably smaller) negative ones. Such a result would at any rate be in accord with their other known capabilities as regards ionisation.

Effect of a Magnetic Field on the Streamers.

In order to test these points still further, I made some observations on the effect of a magnetic field on the course of the streamers. A strong magnetic field was arranged at right angles to the length of the spark, and so that its direction coincided with

* *Loc. cit.*

that of the line joining the spark to the rotating mirror, and a series of photographs was taken with zinc and with magnesium terminals. If the streamers are charged atoms in motion, the theoretical effect to be expected would be that those going up should be deflected in one direction and those going down in the opposite one, thus producing in the photograph a want of symmetry in the course of the streamers from the two electrodes. Such a want of symmetry was indeed found, but the deflections were in the opposite directions to those which would be produced by the action of a magnetic field on negatively charged atoms. The sparks in figs. 3, 4 and 5 were taken in a magnetic field, and they show, in addition to the oscillations already referred to, the want of symmetry in the streamers produced by the field. A close inspection shows also that it is due to the streamers coming off not from the ends, but from the sides of the electrodes. Examination of all the photographs taken under these conditions showed that the effect which really takes place, although there are occasional irregularities, is this: Suppose the top electrode A (in the accompanying diagram) is the cathode, and B the anode, for the initial discharge which gives the air lines, and that the magnetic field is downwards through the paper. The line of the first discharge lies straight across from the point of B to the point of A, and a streamer appears at the point of A. Then, during the back discharge when B is the cathode, the streamer starts from the left-hand side of B, not its point, but the anode is the point of A. The anode can be distinguished in the photographs as faintly luminous. The next streamer starts from the right-hand side of A, the corresponding anode for the discharge being the point of B; and these paths with occasional irregularities are adhered to in the subsequent discharges.



The effect may, I think, be explained without difficulty. In the interval between the first and second discharges the column of ions in motion which marks the line of the first discharge is moved by the magnetic field to one side of the direct line joining the electrodes. In the next discharge the line of maximum electric force is directed towards this ionised column, and the streamer starts from the side of the electrode in the direction of the maximum electric force. This gives an apparent deflection opposite to that which would be looked for as the effect of the magnetic field on the streamer itself. It is very possible that the latter exists when the streamers are once in motion, but I have not been able to find any decisive evidence of it in the photographs; the effect, if existent, is overlaid by the drawing out of the streamers by the mirror. The current itself in the second discharge is, however, certainly deflected by the field, the anode being clearly marked at the *point* of A; thus the ions which carry the current must be deflected by the field along the curved path CD. By the time the next discharge occurs the column of ions has been carried to the right-hand side of the electrodes, and we get the streamer starting from the side of A and the current traversing the deflected path EF.

This displacement of the streamers by a magnetic field I found could be easily observed without using a rotating mirror. Figs. 6, 7 and 8 are photographs of sparks taken between the edges of two zinc plates placed at right angles to each other about a centimetre apart, fig. 6 without, and figs. 7 and 8 with a magnetic field on, in opposite directions in the two cases. In the two latter figures the streamers are displaced along the edge of the plate at the bottom of the figure, and the amount of drawing out being a little irregular some of them can be seen without overlapping. From the upper plate seen end on the streamers come off at the side. By increasing the inductance in the sparking circuit the separation of the streamers can be made still greater; with sodium electrodes and large inductance an enormous drawing out (several centimetres) of the streamers at the side of the spark can be obtained, and the discharge even made to pass in a spiral path between the two electrodes, which is evidently due to the action of a magnetic field on moving ions.

The next point which called for attention was the examination of the streamers in the different monochromatic lights corresponding to the metallic lines of the spark. The measurements of Messrs. SCHUSTER and HEMSALECH, as has already been mentioned, were restricted to the case where no inductance was in circuit with the discharge. Under these conditions the period of the oscillations is so extremely minute that the streamers corresponding to the individual discharges are all superposed on each other, and the details of the structure of the single streamer are completely masked. My first experiments were carried out on similar lines, but with inductance inserted in series with the spark. Although they showed some interesting features, the streamers corresponding to the various lines were so mixed up by superposition on the plate that little detail could be seen. The apparatus was therefore modified in the following way:—A three-prism Hilger spectroscope had the collimator slit and the telescope removed, and the remaining parts were fixed on a wooden stand in such a way that, while the light emerging from the last prism face came out in a horizontal plane, the plane containing the prisms and the collimator was inclined at 45 degrees to the horizontal. The spark, which took the place of the removed slit, was turned round in a plane at right angles to the collimator axis until it made an angle of 45 degrees with the plane of the spectroscope. The light emerging from the prism face in a parallel beam fell upon the rotating mirror with its axis vertical, from which it was reflected direct on to the camera lens. By this arrangement a series of monochromatic images of the spark was produced *en échelon* on the ground-glass screen of the camera when the mirror was stationary, the images being vertical and the dispersion being inclined at an angle of 45 degrees to the horizontal on the screen. The rotation of the mirror causes each of these images to be drawn out in a horizontal direction; and we can thus photograph simultaneously, without much overlapping, a series of images of the streamers in the same spark impressed on the plate by the monochromatic lights of its different metallic lines.

When the metal lines are close together a certain amount of overlapping still takes place, but it is generally possible to distinguish the streamers due to the stronger lines even when this occurs.

Using the spark itself as the source of light instead of its image thrown on the slit of the spectroscope has the advantage not only of simplicity, but also of giving us a truer rendering of the course of the streamers. The course of the spark discharge is often very variable; instead of going straight across from pole to pole, the spark curves round, and its image is very likely to fall off the slit in the centre of the gap; and with a slit in such cases the resulting photograph will give a false impression of both the velocity and the extent of the streamer. By using the spark itself as the source of light, the air lines show the actual path taken by the discharge, and any curvature in them can be taken into account in studying the shapes of the streamers.

With this apparatus, and using the electrical arrangements previously described, about a hundred exposures have been made on sparks with different metals, inductances, capacities, and spark lengths. From the resulting photographs, of which a selection is reproduced to accompany this paper, the behaviour of the different lines, as regards the appearance, velocity, duration, &c., of the streamers, could be studied at leisure. Descriptive notes on the photographs reproduced are given at the end of the paper, and in the following account I shall confine myself to describing the general conclusions which follow from the examination and comparison of the whole series, referring when necessary to the figures in which the best illustrations of them can be seen.

Durations of Lines.

The durations can best be studied quantitatively when there is no inductance in series with the spark gap beyond that of the connecting wires. The period of the oscillations is then extremely small, and the whole spark from an electrical point of view is over before the image is appreciably drawn out on the plate. The fact that nevertheless the metal lines are always drawn out shows that their vibrations last an appreciable time after the stimulus which has excited them has ceased; this time is, moreover, very different for the different lines.

We may take as an example the magnesium spark, fig. 24 (Plate 3), the luminosity of the triplets (5183, 5172, 5167) in the green (nearest the top),* and (3838, 3832, 3829) in the ultraviolet (both unresolved of course), lasts at least four times as long as that of the line λ 4481, which itself has a duration of 16 micro-seconds after the actual spark has ceased. The two triplets are prominent arc lines, 4481 is the well-known spark line, absent from the arc under ordinary conditions. When a little inductance is inserted in the sparking circuit, as in fig. 25, the difference in the duration of the lines makes itself evident in another way. With λ 4481 the streamers are

* The line has almost disappeared in the reproduction, but in the negative shows as an exact but fainter copy of the ultraviolet line at the bottom of the figure.

clearly separated, giving sharp-cut images, but the streamers corresponding to the triplets still overlap and show a confused image with very little detail. Fig. 25 confirms the observations of SCHENCK,* who, also examining the magnesium spark by a rotating mirror, observed that the streamers in it were associated almost entirely with the spark line 4481, the arc lines giving only a diffuse luminescence which lasted in the centre of the spark gap for some time after the actual discharge had ceased. It would be incorrect, however, to infer that the arc lines take no part in the production of streamers; my results show that all the lines of a metal are exactly equal in this respect, and that the clearness of the individual streamers is entirely a question of the varying durations of the lines. By inserting enough inductance in series with the spark, and thus separating the oscillations sufficiently on the screen, the streamers corresponding to the arc lines can always be rendered clear. Thus in fig. 26, where the inductance in circuit has been increased, the streamers in the ultra-violet triplet are distinctly shown.

The difference which we have noted in the behaviour of the arc and the spark lines of magnesium is characteristic of the whole of the metals examined. In every photograph of the inductionless spark the arc lines last from four to six times as long as the spark lines. With a little inductance inserted the spark lines always give rise to sharp and clear cut streamers, in sharp contrast to those of the arc lines, which are diffuse and often overlap, producing a uniform luminosity which lasts some time after the oscillations themselves have ceased. The streamers of the arc lines can, however, always be rendered evident by inserting sufficient inductance in the circuit. The number of oscillations registered on the plate is also generally a little greater for the arc than for the spark lines, say about 14 oscillations as against 12.

A detailed examination of the photographs showed that the spark lines themselves are in many spectra divisible into two classes. We may take as an example fig. 14 (Plate 2) of the bismuth spark. In this figure the three diffuse drawn-out bands represent (counting from the top of the figure) the prominent arc lines 4722, 4122, 3596, and the three sets of strongly-marked and clear-cut streamers lasting throughout nearly the whole duration of the spark can be identified with the groups of spark lines (5208, 5144, 5124), (4340, 4328, 4301, 4259), (3864, 3792, 3757). In addition to these the lines 4560 (just below the highest arc band), 3695, and 3613 (at the bottom of the spark) can be seen. The first streamers of these lines show as intense clearly-marked dots extending from the electrode only a short distance towards the centre of the spark gap. The next streamers are much fainter, and after two or three oscillations only no trace of the lines is visible. I have found lines of this class only in the spectra of the metals aluminium, antimony, bismuth, lead, and tin. (It must be remembered, however, that only the fairly strong lines of the metals can be observed in the photographs.) They are extremely sensitive to the influence of inductance in the spark circuit, and disappear altogether from the spectrum when more than a very

* *Loc. cit.*, p. 129.

small amount is introduced. In the condensed spark without inductance they are usually very bright at the start, but their luminosity dies away much more rapidly than that of the ordinary spark lines. It will be convenient to speak of them as "condensed spark" lines, although it would be premature to suppose that there is any absolute distinction between them and the ordinary spark lines.

Numbers for the durations do not, of course, represent any very definite property of the lines, and only have a value in the absence of more exact knowledge. It is, however, very striking in most spectra how sharply distinguished in duration the lines of the different classes are from each other. In any particular spectrum the lines of each class seem to have all practically the same duration, and there is a big step in its value to that of the other classes. The durations in many cases vary very little from metal to metal, so that it is possible to arrange the metals in groups and to give an average value of the duration which applies fairly accurately to each group of metals and each class of lines. This is done in the following table :—

Metals.	Durations (micro-seconds).		
	Arc lines.	Spark lines.	Condensed spark lines.
Al, Bi, Pb, Sb, Sn	103	16	8·5
Cd, Cu, Hg, Mg, Zn	66	12·5	—
Ca, Na	160	38	—

The actual differences between the classes are likely to be somewhat greater than these numbers would imply, both as a result of the whole of the light of the lines not being shown through under-exposure, and also of the fact that the small but constant time during which the electrical discharge occurs and all the lines glow equally is included in them.

In connection with this evidence it must be observed that the greater duration of lines is not combined with a greater intrinsic brightness at the beginning of the discharge; on the contrary, the intrinsic brightness of the arc lines at the beginning of the discharge is usually much less than that of the spark lines, although, since their light dies away at a slower rate, they may exceed the latter in brilliancy in the photograph of the stationary spark. The difference between the classes is in reality one of the magnitude of the logarithmic decrement of the atomic vibrations corresponding to the lines, the arc lines having a small, and the condensed spark lines a very great, decrement.

Velocity of the Streamers.

It is not an easy matter to obtain values of the velocity of the streamers which will serve as a trustworthy basis in the comparison of different sparks, because the shapes of the streamers in the sparks of different metals are often quite different. Compare,

for instance, the bismuth and the mercury streamers in figs. 14 and 29. The bismuth streamers spread out fanwise from a point, while the mercury ones converge to a point from a broad base.* The velocities also vary somewhat erratically in different sparks with the same metal. Consequently, while numerical values of the velocities are given in the notes on the individual photographs, it would be inadvisable to lay very much stress on them as representing more than very roughly any absolute values characteristic of the metals. They are, however, sufficient to admit some conclusions to be drawn from them. It may be observed that these difficulties do not enter into the comparison of the velocities of the streamers corresponding to the various lines of the *same* spark, for which the photographs are well adapted.

In considering the velocities a distinction has to be drawn, as was first pointed out by SCHENCK,† between the velocity with which the front of the metallic vapour approaches the centre of the spark gap and that of the vapour in the subsequent individual streamers. Thus, taking as an example fig. 26, it will be seen that the first streamer goes only a little way towards the centre of the gap, and then its velocity falls off very rapidly, as is shown by the sudden way in which it curls round and stops short. The next streamer goes a little further, and it is not until after two or three oscillations that the successive streamers become fairly uniform. The velocity with which the front of the metallic vapour approaches the centre of the spark, which is that represented by the locus of the extremities of the streamers, is thus very much less than that of the streamers in the earlier parts of their course. This effect is shown more or less by all the photographs. The probable explanation of it is, I think, that the puff of vapour in the first streamer is rapidly stopped by the resistance of the air present between the poles. The velocities of the streamers quite close to the electrodes are, however, very big, and it is quite possible that they are greater than the molecular velocity of the surrounding air. If this is the case, each puff of vapour will leave a region of smaller pressure behind it, and into this the vapour of the next streamer can be propelled with comparative freedom from friction, and so be propagated further towards the centre of the gap.

This behaviour ot the streamers makes it necessary also to distinguish between the velocity of an individual streamer in the oscillating spark and the velocity of the vapour in the spark without self-induction. In the inductionless spark the streamer is a composite one formed of a number of superposed true streamers, and unless the discharge is absolutely instantaneous and the superposition perfect the velocity

* In photographs taken without a slit the shape of the streamers will be affected by any spreading out sideways which the vapour composing them may undergo as it recedes from the pole. This, and the effects of superposition and under exposure which are referred to below, doubtless account for most of the differences observed in the shapes of the streamers in the sparks of different metals. In so far as these are the causes of the different appearances the measurement of the central line of the streamers will give true values of the velocities.

† 'Astrophysical Journal,' vol. 14, p. 133 (1901).

represented by the locus of the extremities will be different from that of the streamers themselves. There is also another reason why the velocity of the vapour in the inductionless spark should be less than that of the individual streamers. We have already seen (p. 74) reason to believe that the metallic vapour in the streamer is electrically charged, and consequently its motion is alternately accelerated and retarded by the oscillating electric force of the spark. In the spark with sufficient self-induction the streamer can travel as far as the centre of the spark gap during the period the accelerating force only is in play; in the inductionless spark the retarding force will come into play when the streamer has proceeded only a minute distance from the electrode, and its average velocity throughout its whole course will be accordingly diminished. The measurements of the velocities are in entire accordance with these considerations. They show that the velocities of the vapour for the inductionless spark are consistently only about half as great as those of the individual streamers of the same metal in the spark with self-induction.

Messrs. SCHUSTER and HEMSALECH found as a result of their researches that, among the metals they examined, those which possessed the lowest atomic weights gave the highest velocities in the spark. My observations do not confirm this conclusion for the more extensive list of elements which I have examined. For example, sodium, having the lowest atomic weight, shows the lowest velocity of all the metals examined.

I have examined all my photographs in order to find, if possible, evidence of any differences in the velocities which correspond to the different lines of the same metal in the spark, but I have not been able to find any in any case. There are occasional apparent differences, but they can always be adequately accounted for as the result of some portions of the streamers by reason of under-exposure failing to affect the photographic plate.

It is to this cause, I think, that the differences obtained by Messrs. SCHUSTER and HEMSALECH in the velocities of the different lines of bismuth and cadmium must be ascribed. It must be remembered in this connection that the intensity of a streamer, while it may be very great near the poles, falls off rapidly as the centre of the spark gap is approached. Thus the photographed outline of even a single streamer cannot accurately coincide with the actual outline of the luminous vapour, for if we go sufficiently far out the light can not be enough to affect the plate. This effect may indeed be seen in almost every photograph, although in spite of it it is usually apparent that the velocities are the same. A more marked effect will, however, be produced in the photographs of the spark which has no inductance in circuit with it beyond that of the connecting wires. Here, through the minuteness of the periodic time of the oscillations, we are dealing with a number of streamers which are very nearly (although not exactly) superposed on each other. The resulting image on the plate is due to the combined photographic effect of them all. Let us suppose that the brightness of one of the single streamers falls off at such a rate that, at a certain

distance from the pole towards the centre of the spark it is too low by itself to affect the plate. A short distance to one side of this point the second streamer (itself also insufficient to affect the plate) is superposed on it, and the two together will have sufficient intensity to produce a photographic effect. The apparent outline of the luminous vapour will be thus displaced to one side. A little further out, where the individual streamers are still less bright, it will require the combined effect of three streamers to affect the plate, and the apparent limit of the vapour will be displaced still further to the side of the true edge of the first streamer. Thus the apparent velocity of the vapour towards the centre of the spark will over a certain region always be less than the actual velocity, and the extent to which it is so will depend on several circumstances, of which the rate at which the luminosity of the streamers dies away and the period of the oscillations of the spark are two of the chief ones. The period of the oscillations is the same for all the lines in the same spark, but the rate at which the intensity of the light of the streamers corresponding to the various lines dies away is, as we have seen, very different, hence the apparent velocities due to this cause would also be different for the different lines. It is necessary, of course, that the period of the oscillations should be sufficiently large for the streamers to be separated from each other to an appreciable extent, if there is to be produced a measurable change in the velocity by means of this effect. That this is the case in the measurements of Messrs. SCHUSTER and HEMSALECH is, I think, evident from an inspection of their figure 26 of the bismuth spark, where the streamers in the lines of short duration are clearly separated in the photograph. Hence it seems to me that the effects of varying velocities for the different lines which they obtained in their researches may be adequately accounted for in the way described above.

Another point to which attention was paid in the examination of the photographs was the possible existence of differences between the anode and the cathode streamers in each oscillation. It would be interesting, as bearing on their constitution, if any lines were found which were associated with either the anode or the cathode discharge to a greater extent than other lines, but a close scrutiny has not revealed the existence of any such cases. The only case of any difference in the character of the anode and cathode streamers which I have found is that shown in the mercury spark of fig. 29, and the difference here is one which affects all the lines of the metal equally. The cathode streamers are conical in shape and taper to a point, the front edge of the streamer having an inclination which corresponds to a velocity of 530 metres per second, and the back edge to 1100 metres per second. The positive streamer is weaker than the negative one and has its two edges parallel, the inclination of each representing a velocity of 1100 metres per second. The effect is very striking in the negative, and it is not easy to explain it in terms of under-exposure, or, indeed, in any way which at present would not be purely speculative.

Notes on the Photographs.

The following notes refer to the spectrum photographs reproduced in Plates 2 to 4. The earlier figures in Plate 2 have already been described in the text.

The capacity and inductance in the discharge circuit, given in the data for each spark, were measured with a cymometer, and the period of the oscillations from the negatives themselves in terms of the speed of the rotating mirror. The latter was measured before and after each spark by timing the rotations of a lower wheel of the gearing, which rotated with the $\frac{1}{120}$ part of the angular velocity of the mirror itself. The periods agree with their calculated values, as a rule, to within one or two per cent. Measurements of the durations of the lines are recorded for the "inductionless" spark only, and they represent the times from the beginning of the discharge during which a photographic effect is distinguishable on the negative. The inductance of the connecting wires in the inductionless spark was also measured with the cymometer. It amounted roughly to 0·25 microhenry. This would make the theoretical period of the oscillations from 0·3 to 0·46 micro-second according to the capacity in circuit. This is in itself inappreciable, but if there were, say, a dozen oscillations the drawing out in the photograph would be easily observed. This is in accordance with the photographs which show an appreciable broadening of the base of the metal lines in most of the inductionless sparks, but this has not been deducted from the durations.

The negatives were taken on Wratten's "Verichrome," in some cases on their "panchromatic" plates, and the spectrum recorded extends from about λ 6300 to λ 3500. In the reproductions the top of each figure always represents the red end of the spectrum. Only the stronger lines in the spectrum are referred to in the lists below. The negatives reveal many of the weaker lines in the spectrum, most of which have been identified, but as they do not show in the prints they are not referred to except in exceptional cases. The streamers are often composite in character, a strong streamer being formed by the overlapping of several weak lines close together. Groups of lines which combine to form a single set of streamers are enclosed in brackets.

The vertical ordinates are the same in all the photographs, but were reduced by the camera in the ratio of 0·38. On the other hand, the photographs have been enlarged $1\frac{1}{2}$ diameters in the reproduction, thus the figures represent the relative lengths of the sparks, but a spark length 0·57 cm. in the figure corresponds to an actual spark length of 1 cm.

The velocities were determined by careful measurements on the negatives by a reading microscope of the inclination of the streamers with respect to the air lines of the spark. They refer to the front edge of the metallic vapour in the inductionless spark and to the centre of the streamers in the sparks with self-induction. Numbers for the velocities are only recorded when the streamers were sufficiently clear in the negatives to enable a fairly definite measurement of several streamers in the same spark to be made (the detail of the streamers which permitted the measurements has sometimes disappeared from the reproductions). The numbers given represent the average velocity over the first two millimetres of the path; the initial velocities are probably two or three times as great, but are very difficult to measure.

Aluminium.

Fig. 9. Capacity 0·0223 microfarad, no inductance, velocity 350 metres per second.

Fig. 10. Capacity 0·0223 microfarad, inductance 95 microhenries, period 8·95 micro-seconds, velocity 650 metres per second.

The only arc line of aluminium, the doublet (3961, 3943), shows plainly as lasting much longer than any of the others, its duration in fig. 9 being 100 micro-seconds. In fig. 10 the streamers in it can be distinguished, but the whole spark gap is filled with more or less light which lasts in the centre long after the actual spark has ceased. The lines of next longest duration (20 micro-seconds) are the group of spark

lines (3612, 3600, 3584) which forms the strong diffuse streamers at the extreme bottom of the spark. The remaining lines visible in the prints are the groups (4622, 4611) at the extreme top of the spectrum, with the sharp strong streamers of (4529, 4511, 4478) just below it, an unidentified line of approximate wave-length 4200 a little above the arc line, and (3713, 3701) a little below it. These groups possess a duration of 12 micro-seconds and they show streamers which are more sharply defined and which die out more rapidly than those of the first-mentioned group, but the distinction between spark and condensed spark lines appears to be less marked with aluminium than with the other metals.

Bismuth.

Fig. 11. Capacity 0·0223 microfarad, no inductance, velocity 220 metres per second.

Fig. 12. Capacity 0·0223 microfarad, inductance 40 microhenries, period 6·0 micro-seconds, velocity 600 metres per second.

Fig. 13. Capacity 0·0223 microfarad, inductance 95 microhenries, period 9·14 micro-seconds.

Fig. 14. Capacity 0·0223 microfarad, inductance 170 microhenries, period 11·7 micro-seconds.

The bismuth figures are described in the text, p. 78. The streamer dots apparent in the course of the arc line bands 4722, 4120 are not due to the arc lines but to spark lines, (4797, 4750) and 4080, which show through them. The equality of the velocities in the streamers corresponding to the various lines is plainly shown in the negatives. The streamers in the condensed spark lines are fan-shaped, they are quite narrow at the pole and spread out as they recede from it, while those of the other lines have a broader base. This is interesting as it shows that the vibrations of the condensed spark lines are only induced just at the very centre of the oscillation period when the current and electric force are at their maxima.

Durations in fig. 11:—

Arc lines 105 micro-seconds, spark lines 18 micro-seconds, condensed spark lines 9 micro-seconds.

Cadmium.

Fig. 15. Capacity 0·0106 microfarad, no inductance, velocity 450 metres per second.

Fig. 16. Capacity 0·0223 microfarad, inductance 95 microhenries, period 8·7 micro-seconds, velocity 1000 metres per second.

Fig. 17. Capacity 0·0223 microfarad, inductance 95 microhenries, period 9·2 micro-seconds.

Fig. 18. Capacity 0·0171 microfarad, inductance 260 microhenries, period 13·2 micro-seconds, velocity 850 metres per second.

All the lines of cadmium show the streamers plainly, but there is a great contrast between the sharp streamers of the spark lines and the blurred ones due to the lines which persist in the arc. In spite of their different character the uniformity of their velocities can be seen in fig. 16.

The following are the more prominent lines visible:—

Arc lines. Duration 67 micro-seconds.

5085, 4800, 4678. Partly overlapping blurred streamers.

(3613, 3610). Strong diffuse streamers at the bottom of the spark. Those of (3467, 3466), much fainter, but in the negatives showing an exactly similar appearance to the former, can be just distinguished below them.

Spark lines. Duration 10 micro-seconds.

(5378, 5337). At the extreme top of the spark. The streamers are very sharply defined and visible near the poles only. There appear to be no condensed spark lines.

Calcium.

Fig. 19. Capacity 0·0106 microfarad, no inductance, velocity 780 metres per second.

Fig. 20. Capacity, 0·0223 microfarad, inductance 260 microhenries, period 15·1 micro-seconds, velocity 1700 metres per second.

Calcium is remarkable for both the great velocity and duration of its streamers. The lines visible in the photographs are all prominent arc lines, and they give rise to a general blur which partly masks the streamers even at high inductances. The only exception is the double line (3737, 3706), which has a much smaller duration than the others.

The four bands visible in fig. 20 can be identified in the negatives with the following lines or groups of lines:—

(1) 5587, 5348, 5269. Duration 170 micro-seconds.

(2) (4454, 4434, 4425), (4319, 4302, 4289, 4282), 4227. Duration 146 micro-seconds.

(3) 3968, 3933. Duration 120 micro-seconds. These show the streamers plainly, although the spark gap is filled with a general light.

(4) 3737, 3706. Duration 40 micro-seconds. These lines give quite sharp streamers which are overlapped by a general blur due to the strong arc line (3644, 3631, 3623), the difference in the behaviour of the two lines being very apparent.

Lead.

Fig. 21. Capacity 0·0223 microfarad, no inductance, velocity 190 metres per second.

Fig. 22. Capacity 0·0223 microfarad, inductance 40 microhenries, period 6·3 micro-seconds.

Fig. 23. Capacity 0·0223 microfarad, inductance 260 microhenries, period 15·0 micro-seconds, velocity 400 metres per second.

The following lines are visible:—

Arc lines. Duration 115 micro-seconds.

(4062, 4058, 4019).

3740, (3683, 3671), 3640, 3572.

These form the two drawn-out bands in which traces of streamers can be seen in fig. 23; the individual lines cannot well be distinguished in the prints.

Spark lines. Duration 16·5 micro-seconds. Sharp streamers repeated throughout the spark.

(5608, 5545), 5372. Very faint at the extreme top of the spectrum.

4386, 4246. The two sets of strong streamers just above the first arc band.

Condensed spark lines.

(3854, 3842, 3833). The streamer corresponding to this unresolved group forms an intense white dot in fig. 21, a streamer repeated once only in the negative of fig. 22, and it has entirely disappeared in fig. 23. The three photographs show how very sensitive the lines of this class are to the influence of self-induction.

Magnesium.

Fig. 24. Capacity 0·0106 microfarad, no inductance, velocity 450 metres per second.

Fig. 25. Capacity 0·0223 microfarad, inductance 40 microhenries, period 6·0 micro-seconds, velocity 800 metres per second.

Fig. 26. Capacity 0·0223 microfarad, inductance 170 microhenries, period 11·5 micro-seconds, velocity 800 metres per second.

See p. 77. The arc lines in the inductionless spark last 60 micro-seconds, the spark line 4481 only 15 micro-seconds. The anode discharge is very marked in magnesium, and at the beginning of the

discharge is nearly as powerful as that of the cathode. It is worthy of note that, in spite of this, in the line 4481 there is a distinct separation between the anode and cathode streamers towards the end of the discharge. This shows that the streamer corresponding to this line is only produced when the current and electric force exceed a certain minimum value. The same effects are to be seen in the spectra of calcium, lead, and mercury.

Mercury.

Fig. 27. Capacity 0·0106 microfarad, no inductance, velocity 670 metres per second.

Fig. 28. Capacity 0·0106 microfarad, inductance 40 microhenries, period 4·1 micro-seconds, velocity 890 metres per second.

Fig. 29. Capacity 0·0223 microfarad, inductance 170 microhenries, period 12·2 micro-seconds.

The sparks were taken from poles of amalgamated zinc, and show the lines of both metals, as follows :—

Arc lines. Duration 58 micro-seconds in fig. 27, diffuse streamers in fig. 28.

(5790, 5769), 5461, 4359, 4047, 3650 due to mercury.

4809, 4721 due to zinc, but behaving quite similarly to the mercury as regards duration and velocity.

Spark lines.

3984 (mercury). The streamers differ very little in sharpness from those of the arc lines in fig. 28. In fig. 29 they are sharper and considerably diminished in intensity.

(4924, 4911) (zinc). Sharp streamers in fig. 28, which disappear with the increased inductance in fig. 29.

Zinc.

Fig. 30. Capacity 0·0171 microfarad, inductance 40 microhenries, period 4·8 micro-seconds.

The arc lines 6363 at the top of the figure (very faint), and 4809, 4721, 4609, in the centre in both cases form blurred bands overlapping the sharp streamers of the spark lines (6102, 6022) and (4924, 4911) which show through them.

Sodium.

Fig. 31. Capacity 0·0223 microfarad, no inductance, velocity 130 metres per second.

Fig. 32. Capacity 0·0223 microfarad, inductance 95 microhenries, period 9·1 micro-seconds, velocity 440 metres per second.

The only line clearly visible is the D line, which has a very great duration (170 micro-seconds in fig. 31). In spite of this it shows moderately well-defined streamers in fig. 32. There is a striking difference between the air-line spectrum in the two sparks in this photograph, the right-hand one showing a number of fine lines which are not air lines, and which are possibly due to the spark having occurred through sodium vapour.

Tin.

Fig. 33. Capacity 0·0171 microfarad, inductance 40 microhenries, period 5·0 micro-seconds, velocity 800 metres per second.

The two blurred bands which last in the centre of the spark gap for some time after the oscillations have ceased are the two strong arc lines 4525 and 3801. The streamers apparent in the earlier parts of their courses are probably due to the spark lines 4586 and 3861, and not to the arc lines themselves. The spark lines, like those of bismuth, although not to the same extent, vary considerably in the number of repetitions which their streamers undergo. The strongest of the condensed spark lines, which shows very brightly and as of very short duration in the inductionless spark, forms the bright but very rapidly fading streamers just below the lower arc line (3745 probably). The well-defined streamers at the top of the figure are those of the lines 5801, (5589, 5563), 5333.

Antimony.

Fig. 34. Capacity 0·0223 microfarad, inductance 40 microhenries, period 5·9 micro-seconds, velocity 1300 metres per second.

The antimony lines, like those of bismuth, fall into three well-marked classes. The arc lines 4033, 3637 show as drawn-out bands filling the whole spark gap. 4352, 4265, and unidentified lines with approximate wave-lengths 3600, 3400, and 3320, belong to the condensed-spark class, the first streamer being very marked and the rest rapidly fading away. The remainder appear to be ordinary spark lines, but are difficult to identify.

Copper, Nickel, Platinum. Figs. 35, 36, 37.

These metals show no well-marked lines, and the faint lines are so numerous and close together that they are not resolved in the photographs. The oscillations are represented by long lines throughout the spectrum, which only show at the top of the spark. The reason of this is probably that the streamers of the individual lines are too weak to affect the plate, and that the direction of the drawing out of the spark by the mirror is such that at the top of the image the streamers of neighbouring lines fall with their lengths over each other, and being thus superposed give a luminosity sufficient to register itself. At the bottom of the image the streamers are broadside on and are not superposed. The effect is observable more or less in all the photographs.

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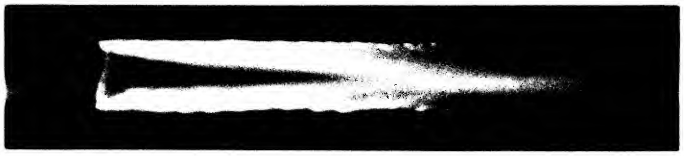

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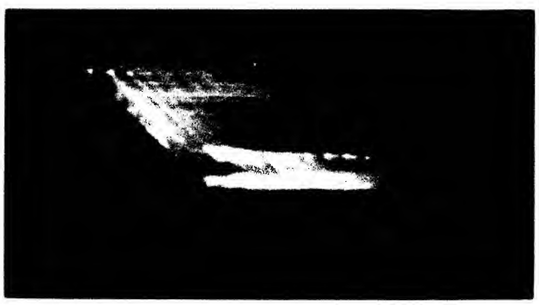

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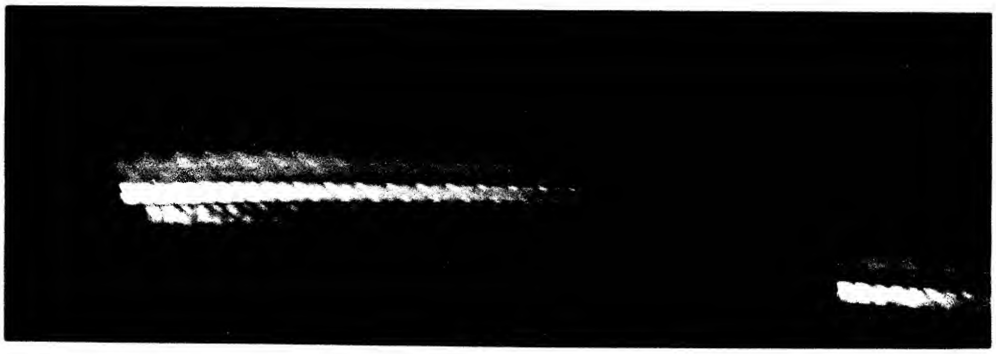

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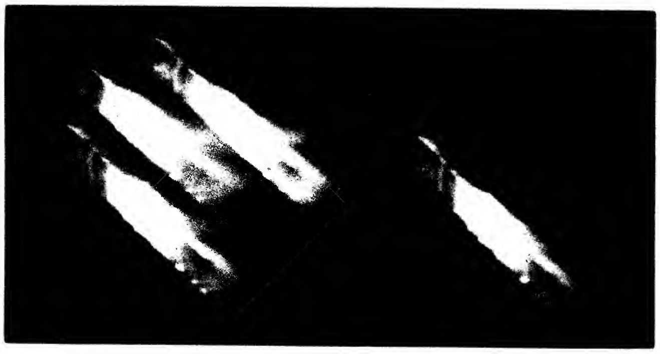

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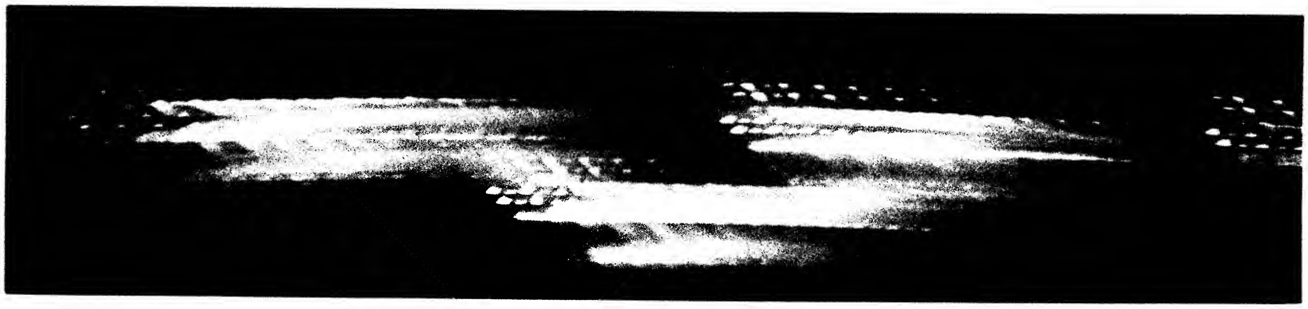

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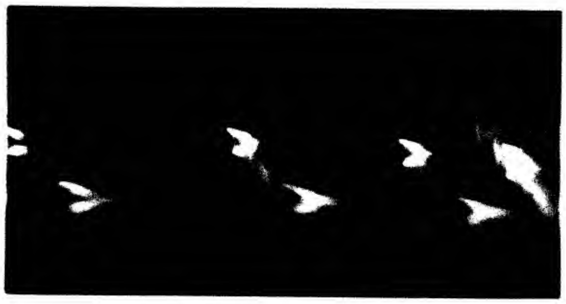

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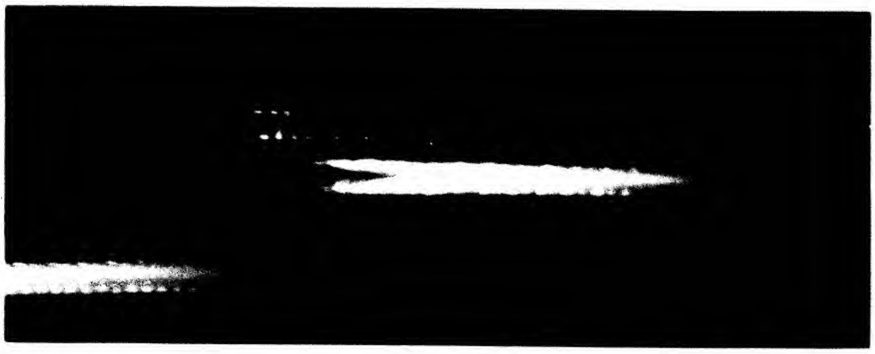

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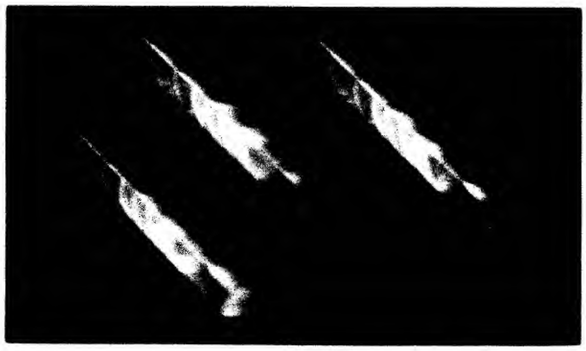

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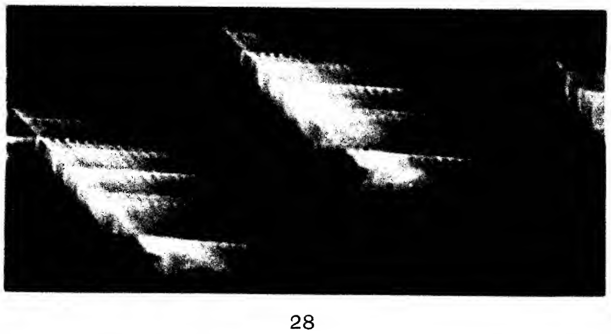

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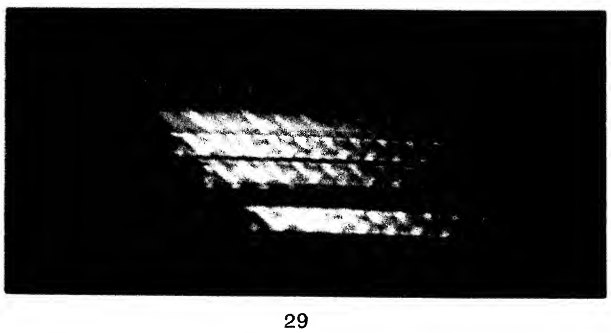

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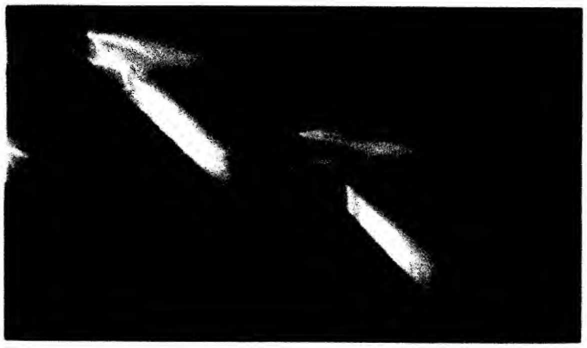

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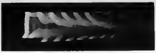
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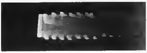
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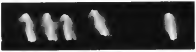
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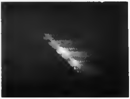
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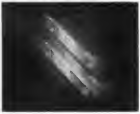
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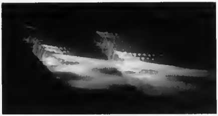

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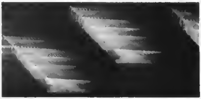

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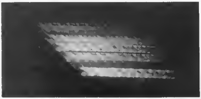

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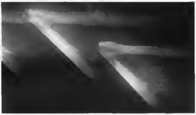

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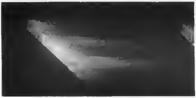

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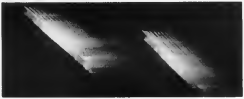

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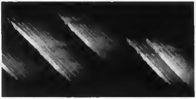

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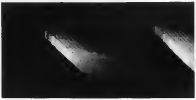

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